RECONNAISSANCE STUDIES OF A PILOT CARBON SEQUESTRATION SITE IN THE CENTRAL APPALACHIANS OF WEST VIRGINIA

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ABSTRACT: The U.S. Department of Energy is planning a pilot carbon sequestration effort in an unminable coal seam in northern West Virginia. CO_2 will be injected into the Upper Freeport coal, which lies approximately 1400 feet beneath the surface in Marshall County, West Virginia. The objectives of the pilot test are to enhance coal bed methane production through CO_2 injection and, at the same time, to sequester significant amounts of injected CO_2. Effective sequestration requires that injected CO_2 remain trapped for several thousand years; thus, assessment of reservoir integrity is a critical component of the sequestration effort. As part of the site assessment we examined subsurface well data and various satellite images, digital elevation data, and aerial photographs to characterize site geology and provide a preliminary assessment of the integrity of the sequestration interval. Bedding dip in the area is less than 1 degree. The pod-like distribution of the coal in this area makes it unminable.

This reconnaissance effort incorporated a comprehensive lineament analysis to identify potential fracture zones or faults in the area. Lineament orientations are clustered into orthogonal strike and dip sets with two additional sets forming an acute angle in the dip direction. Lineament orientations are also consistent with surface fracture and coal cleat trends mapped in the area. Lineaments mapped in the vicinity of the pilot site are dominated by a N75E (shear) trend. The association of lineaments with actual fracture zones or faults will be confirmed in future electromagnetic conductivity and seismic surveys of the pilot site. The combined remote sensing and geophysical studies are intended to determine whether relatively high permeability pathways exist along which displaced methane or injected CO_2 might migrate to the surface. Geochemical monitoring activities will be concentrated near likely pathways. is confirmed.

Key words: carbon sequestration, monitoring and verification, remote sensing, lineament analysis, fracture analysis, enhanced coal bed methane recovery

BACKGROUND - GEOLOGIC SEQUESTRATION OF CO_2

The steady increase of atmospheric CO_2 concentrations during the last century and its correlation to a gradual increase in average global temperature provide the impetus to develop technologies that reduce CO_2 emissions and reduce or eliminate further increases in atmospheric CO_2 concentration. Reduction of CO_2 emissions can be achieved through more efficient energy conversion, use of carbon-free energy sources, or through capture and sequestration of CO_2 generated from fossil fuel usage before it reaches the atmosphere (U.S. Department of Energy 1999). Sequestration of CO_2 in underground geologic formations offers considerable potential for success. The likelihood of success is inferred from the fact that hydrocarbons in gaseous form have been preserved in geologic formations for millions of years prior to their present-day extraction for energy consumption.

Geologic sequestration has been proposed in three different geologic settings including coal formations, deep saline aquifers and depleted oil and gas fields. The U.S. Department of Energy currently sponsors enhanced coal bed methane recovery efforts in the San Juan basin. Approximately 4 million cubic feet per day of CO_2 are being injected to enhance coal bed methane recovery from the northern San Juan basin Allison Unit operated by Burlington Resources. Preliminary results indicate that CBM production is enhanced by 75-90% (Byrer 2002). To date, 2.5 Bcf of CO_2 have been injected in the field with little or no breakthrough. A major carbon sequestration effort is also underway in the Weyburn oil field in southeastern Saskatchewan (Brown et al. 2001). The sequestration effort includes acquisition of significant baseline data in the form of 3D seismic, cross-well VSP, and geochemical sampling. Baseline surveys will provide key reference points for the evaluation of long-term storage capacity and storage verification. In southeastern New Mexico, DOE, Sandia, and Los Alamos National laboratories along with industry partners Strata Production and Pecos Petroleum are undertaking another carbon sequestration pilot test in a depleted oil field (Westrich et al. 2001). Their study also incorporates baseline geophysical surveys. Site monitoring activities include pre-injection analysis of shallow soil gas sampling using sorbents and differential absorption LIDAR (Light Detection and Ranging) measurements. Tracers used at the New Mexico site consist of perfluorinated carbons introduced into the CO_2 flood. DOE is also sponsoring another project with the objective to design and ready for permitting an experimental CO_2 injection well near New Haven, West Virginia on an American Electric Power plant site. Battelle Memorial Institute is undertaking the study. They plan to inject CO_2 into the deep Cambrian saline sands of the Mt. Simon Formation deposited on the Precambrian basement surface in this area. The Battelle study includes plans for baseline geophysical studies and a comprehensive analysis of borehole logs and core in a 10,000 foot well.

In the pilot test discussed in this paper, CO_2 will be injected into the Upper Freeport coal at a depth of about 1400 feet in Marshall County, West Virginia. CO_2 will be injected into four horizontal wells located at the center of a one-kilometer square test site. Methane production will take place in four lateral wells surrounding the site perimeter. The Upper Freeport Coal in this area is considered to be unminable.

The current study reports on preliminary site characterization efforts and incorporates subsurface mapping using limited exploratory well data, remote sensing lineament analysis and field measurements of systematic fracture orientations in areas surrounding the site. The major objective of this effort is to locate structures that might jeopardize the integrity of the sequestration interval and to help guide the location of monitoring activities at the site. Site monitoring will include soil gas and groundwater analysis for CO_2 and by-product reactions. The preliminary geologic characterization of the site reported on here will be followed by geophysical surveys of the site (electromagnetic and seismic) to measure physical attributes of lineaments observed at the site and gain a more detailed look at subsurface geology.

Regardless of the approach being used to sequester CO_2, it is necessary to verify that injected CO_2 remains underground. Carbon sequestration sites must be monitored to detect leaks should they occur and thus defeat the purpose of the CO_2 sequestration effort. Site monitoring is also critical to gaining public acceptance of sequestration activities and providing assurance that these efforts do not represent an environmental hazard.

Concern at the West Virginia site, is that injected CO_2 might escape back into the earth's atmosphere along fracture zones or faults. If these zones exist, they may also represent zones of enhanced permeability along which CO_2 leakage could occur. Placement of monitoring systems near likely migration pathways such as fracture zones and faults will provide the best chances for detecting leakage or verifying that it does not occur.

Fractures play an important role in coal bed methane production and could have adverse effects on long-term CO_2 storage. Ambrose and Ayers (1991), in their study of the geologic controls on occurrence and producibility of methane from the Fruitland Formation in the Cedar Hills area of the San Juan basin, note that maximum daily production rates are greatest where coal beds have been folded along a synclinal axis. They note that fractures associated with these folds may increase permeability and therefore enhance production. Tremain et al. (1991) also note that orientation, spacing, and mineralization of coal cleats create permeability anisotropy that influences methane production potential in the San Juan basin. Although CO_2 storage in coal is primarily through CO_2 adsorption into the coal matrix, significant fracture permeability in the overlying strata could facilitate escape of unadsorbed CO_2.

Analysis of aerial photographs and satellite imagery is often employed to map lineaments and identify potential fracture zones. Baumgardner (1991), for example, conducted an extensive photolineament study in the San Juan basin of New Mexico and Colorado to evaluate the relationship of lineaments to coal bed methane production in the basin. The San Juan basin area has been the focus of several lineament studies. Photolineaments were mapped in a 1969 study (Kelley and Clinton 1960). Knepper (1982) mapped lineaments from Landsat imagery and made an important distinction in his work by associating certain lineaments with gravity and magnetic anomalies and dike swarms. Decker and others (1989) analyzed Landsat and aerial photography in the Cedar Hills area. They reported that linear features observed in imagery were parallel to the coal cleat directions and sub parallel to open fractures in core from a well in the Cedar Hills, New Mexico area. Work by Wandrey (1989) incorporated field checking and revealed that some aerial photographic trends corresponded to joints on larger scale photos. Analysis of a variety of black and white, color infrared, and Landsat TM (bands 7,4 and 2) of the Cedar Hills area was undertaken. The area has been thoroughly studied using a variety of imagery; however, Baumgardner (1991), in his attempts to integrate observations from the various studies found little agreement between the various studies. More than 95% of the lineaments mapped in four separate studies did not coincide.

In our research we analyze a variety of remote sensing data to identify potential fracture zones. Directional analyses of lineaments mapped in imagery are compared to fracture trends mapped in the study area. As part of our ongoing work, we plan to follow the lineament identification process with ground-based geophysical observations of lineaments that intersect the pilot site. The ground-based geophysical surveys will verify whether changes in subsurface physical properties are associated with lineaments at the pilot site. Several studies demonstrate that this approach yields more reliable interpretation of lineament significance (e.g. Silbaugh 1985; van Lissa et al. 1987; Rumbens 1990; Werner 1996; Spratt 1996; Powers et al. 1999). The present study also incorporates analysis of satellite radar imagery acquired for this project into the lineament mapping process. Radar imagery is often used in the energy exploration industry to map surface geology (Dodge et al. 1999).

METHODS

We designed a remote sensing study to identify locations of possible fracture zones and faults at a pilot carbon sequestration site in northern West Virginia area (Fig. 1). The main focus of the preliminary remote sensing study

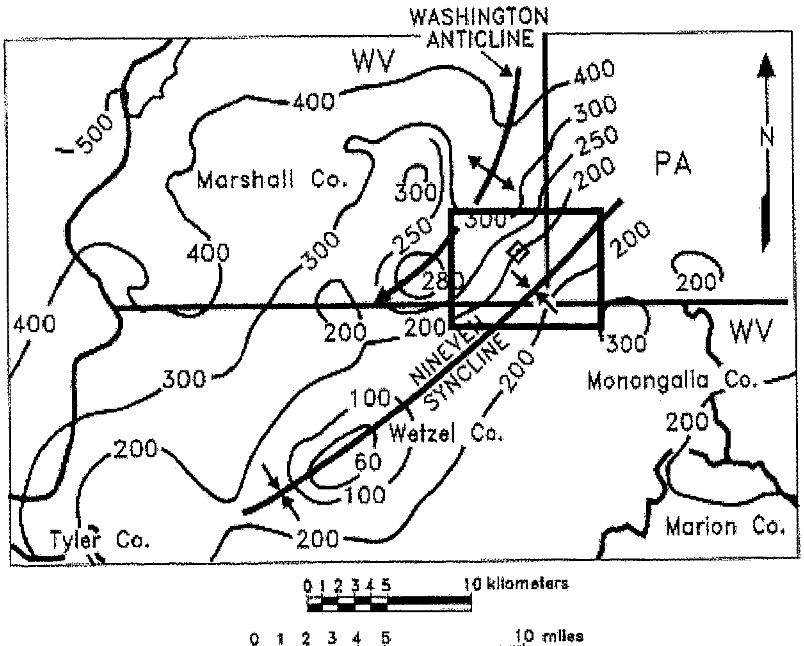

Figure 1. Location of the carbon sequestration pilot site is shown on the regional structure map of the Pittsburgh Coal (WVGES Interactive Coal Bed GIS Mine Maps Web Site, http://ims.wvgs.wvnet.edu/coalims.htm). Structure contours on the coal are also shown. Contour interval varies from 30 to 100 feet.

was to map lineaments and compare their directional attributes to surface fracture orientations and published orientation data on coal cleat trends in the region. Satellite radar images were collected for this project using the Canadian Radarsat Inc. satellite. In addition to the analysis of radar data, lineaments were also mapped using Landsat TM, SPOT, digital orthophotoquads, digital elevation data (DEM) and low altitude aerial photography.

Radar imagery is often employed in lineament identification studies, and is generally considered an excellent tool for mapping surface structures and lineaments. Radar images are compiled from reflected radar waves emitted by the satellite. Thus relief shading is not dependant on sun angle, and the illumination angle can be adjusted to suit project needs. In addition, since clouds are transparent to radar waves, radar images provide an unobstructed view of the surface. In highly vegetated areas the radar signal is dominated by interaction with surface vegetation rather than the ground surface (Sabins 1996). The radar image also provides excellent information about ground surface features. In forested areas, for example, the forest canopy often parallels the ground surface so that reflections from the forest canopy provide information about surface irregularity. In areas not covered by forest canopy, the radar image reveals differences in type of cover, growth rate, and density of growth. As a consequence the radar signal provides information associated with the surface contour and surface roughness. Radar data collected for this study were recorded at 25 meter and 8 meter pixel resolutions. Sabins (1996) notes that the large resolution cell of radar is an asset to structural interpretation because it acts as a filter to remove high frequencies and improve resolution of low frequency geologic "signals."

Surface roughness, surface slope and incidence angle, dielectric properties, and water content control the intensity of backscattered radar waves. As Sabins (1996) notes, increased water content produces increased backscatter of the radar signal. The various characteristics of the radar signal noted above make radar an excellent tool for identification of possible fracture zones and faults. In the temperate latitudes of West Virginia, zones of increased fracture intensity are more likely to be coincident with variations in near-surface water saturation, density of vegetation, and preferential weathering, all of which are potentially identifiable in the reflected radar signal. Processing of the radar image for lineament interpretation was minimal and consisted of inverted linear contrast enhancement.

As part of the study, we also undertook an analysis of Landsat 7 ETM (Enhanced Thematic Mapper) multispectral imagery. The Landsat scene used in this study was obtained from the "Chesapeake Bay From Space" web site at http://chesapeake.towson.edu/data/download/fullscenes.asp. The Landsat image provides observations of the earth's surface at 7 different wavelengths: 3 visible wavelength bands (red, green, and blue), three reflected infrared bands and one thermal infrared band. RGB (red, blue, and green) images compiled from different combinations of the Landsat bands provide diverse views of the earth's surface features. The thermal IR band is generally not used unless nighttime images are available. The Landsat 7 ETM pixel size is 25 meters.

As noted above Landsat data were used to map lineaments associated with coal bed methane production in the Cedar

Hills area of the San Juan basin (Decker et al. 1989). Rasco (1999) reported on the analysis of Landsat imagery from the southern Powder River Basin in Wyoming. Rasco noted that directional analysis of Landsat lineaments attributed to topographic features in the basin revealed similarity to structural trends associated with the later stages of the Larimide Orogeny. Complimentary analysis of DEM and digital topography lineaments by Rasco supported that finding. Directional analysis of Landsat lineaments attributed to tonal features associated with surface vegetation revealed the presence of lineament orientations believed to be consistent with early Larimide structural trends.

Warner (1997) noted that Landsat lineaments mapped along the Burning Springs and Volcano oil fields in West Virginia appear to have structural significance. In Warner's study, cross-strike lineaments were highly correlated with soil gas concentrations. While lineaments appeared to have little relationship to natural open flow rates, highest annual production rates are found closest to lineaments.

In the present study, numerous band combinations were examined. Rasco (1999) assigned bands 4, 3 and 1 to the red, green, and blue colors and employed Laplacian edge enhancement to the image used in his study of lineaments in the Powder River Basin. In our analysis we tested the 4, 3, and 1 band RGB combination and used the Laplacian edge enhancement filter. Numerous band combinations were tested. Tests indicated that an image compiled using TM band 3 for red, band 4 for green, and band 5 for blue, with linear contrast enhancement provided effective lineament enhancement in the Landsat view of the study area.

SPOT panchromatic data are another form of satellite imagery that offer higher ground resolution than Landsat. SPOT imagery was obtained from the West Virginia State GIS Technical Center at http://wvgis.wvu.edu/data/datas et.php?action=search &ID=90. The SPOT panchromatic imagery provides a view of ground patch areas 10 meters on a side. SPOT imagery were orthorectified using control points from USGS 7.5 minute quadrangles. The SPOT panchromatic sensor responds to visible and near-infrared wavelengths in the 0.51 to 0.73 micrometer range. SPOT is often used in combination with Landsat because of its smaller ground resolution cell. Sabins (1997) noted that Landsat is often used for preliminary geologic mapping in regional oil exploration projects to identify subareas with exploration potential. Prospective subareas can then be mapped in greater detail using SPOT. In our study, processing of the SPOT image for lineament interpretation consisted simply of inverted grayscale equalized contrast enhancement.

The highest resolution images used in the present study were digital orthophotoquads (DOQ). The DOQ provides a map-like view of the earth's surface in which distances and perspectives associated with the camera viewing-angle have been eliminated. The orthophotoquad provides one-meter pixel ground cell resolution. Orthophotos used in this study were compiled from high-altitude color infrared aerial photographs. The color infrared image is compiled from three wavelength bands spanning the 0.5 to 0.9 micrometer range that correspond to visible green and red, and the near infrared. A yellow filter is used to absorb blue light and reduce high altitude haze. The orthophotos are derived from the U. S. Geological Survey coordinated National Aerial Photography Program database. Photographs are taken at an altitude of 20,000 feet above mean terrain. DOQ's used in this study were obtained from the West Virginia GIS Tech Center Clearinghouse (see http://wvgis.wvu.edu/data/data.php). Inverted linear contrast enhancement was applied separately to each band prior to lineament interpretation.

Analysis of older black and white aerial photography was also undertaken in this study. The black and white aerial photo is often used in fracture trace identification studies (e. g. Silbaugh 1985; van Lissa et al. 1987; Powers et al. 1999). In the present study, analysis of aerial photography was restricted to examination of a 1938 black and white aerial photograph of the pilot site and surrounding area. The West Virginia Geological Survey provided aerial photographs of the area in digital and paper format. The digital black and white image was orthorectified and lineaments were picked using minimal contrast enhancement.

We also incorporated analysis of digital elevation data (DEM) in our study. We obtained DEM data over the Marshall Co. pilot site from the West Virginia GIS Technical Center. Processed digital elevation data were used to locate and map flow-paths. Lineament analysts consider topographic lineaments to be good indicators of possible fracture zones and faults. Computer identification of flow path trends is an objective way to determine topographic lineament trends. Our study included a directional analysis of computer derived surface flow-path orientations derived from the digital elevation data.

GEOLOGIC BACKGROUND AT THE MARSHALL COUNTY SITE

The pilot sequestration site is located in the southeastern corner of Marshall County, West Virginia (Fig. 1). The area lies in the gently deformed Central Appalachian foreland over the Rome trough (a deeply buried Cambrian age failed rift or aulacogen). Deformation in this area probably consists of minor detached folds and late stage flexure related to reactivated basement structures within the trough. The pilot site occupies an area approximately 1km or 3000 feet on a side and is located on the southeast limb of the Washington anticline just northwest of the axis of the Nineveh syncline (Figs. 1 and 2). The regional structural context of the area is inferred primarily from the structure

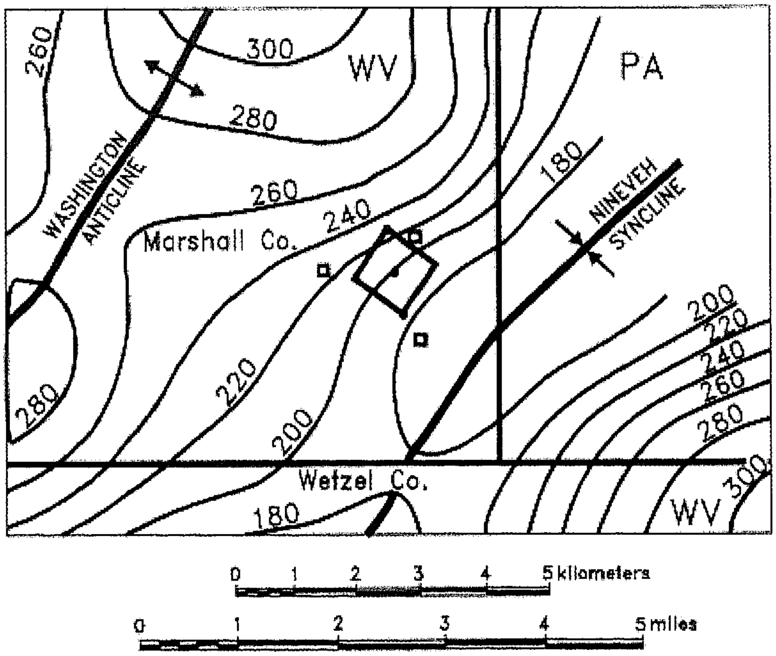

Figure 2. Structure contours on the Pittsburgh coal are shown in the vicinity of the pilot site. Contour data were taken from the WVGES Interactive Coal Bed GIS website database. The contour interval is 20 feet.

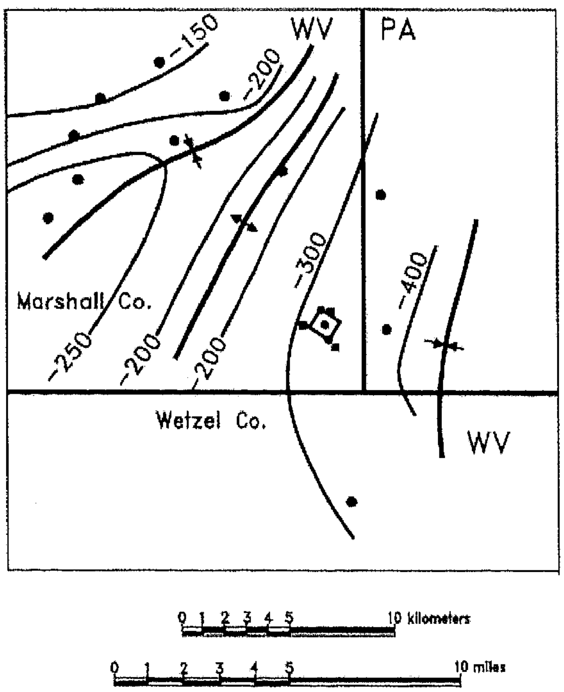

Figure 3. Structure contours on the Upper Freeport coal in the vicinity of the pilot site. Dots show locations of well control points. Contour interval is 50 feet.

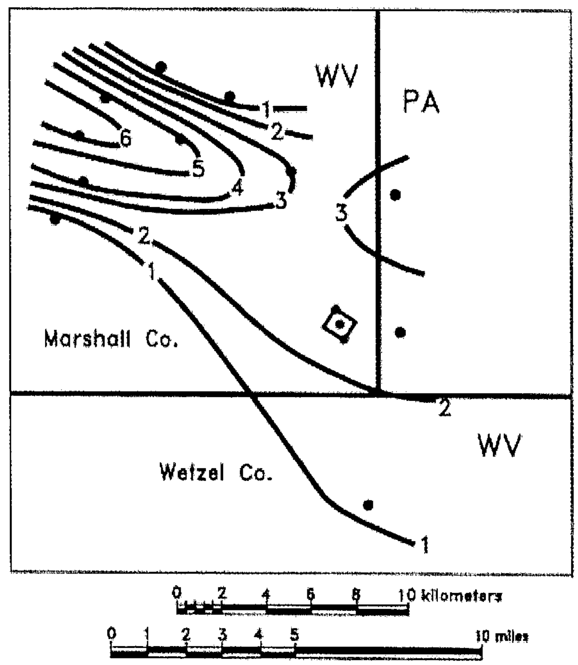

Figure 4. Isopach map of the Upper Freeport coal in the area surrounding the pilot site. Dots locate exploratory well control points. The contour interval is 1 foot.

of the Pittsburgh coal.

DOE will sequester CO_2 in the Upper Freeport coal at the top of the Allegheny Formation. The West Virginia Geological and Economic Survey provided strip logs for 11 non-proprietary coal exploration wells in the surrounding area. These wells are located within approximately 12 miles of the site (Fig. 3). Hand contouring of these 11 control points reveals the general outlines of the Nineveh syncline and Washington anticline at depths of approximately 550 feet beneath the Pittsburgh Coal (Fig. 3). Regional dip across the pilot site is less than 0.5 degrees.

The isopach map of the Upper Freeport coal (Fig. 4) reveals considerable variation in thickness throughout the area. Within the vicinity of the pilot site the Upper Freeport varies between 2 and 3 feet thick. The coal is missing in places where it has either been eroded or was not deposited. An isopach map of the sands immediately above the Upper Freeport (Fig. 5) suggests the general outlines of a channel system that may cut through the area. The channel may have scoured down into the Upper Freeport, completely removing it in places. In some wells the sand is in direct contact with the coal and is assumed to have partially eroded the earlier coal deposit.

SURFACE FRACTURE DATA

Measurements of surface fracture data provide important context for the evaluation of lineaments mapped in imagery. A total of 451 fracture trends were measured at 31 outcrops exposed along roads in the area surrounding the pilot site. The rose diagram of length-weighted fracture trends (Fig. 6) reveals some preferred orientations. Application of Rayleigh's test suggests there is a very low probability (less than $\alpha = 0.01$) that the observed fracture orientations could have been sampled from a uniform distribution.

Fracture trends appear to fall into three clusters with vector means of N74W, N26E, and N71E. The 95% confidence limits on each of these clusters are between ± 2 to 3 degrees. The t-test suggests that the vector means of individual fracture sets differ significantly at $\alpha << 0.001$ for the one-tailed test.

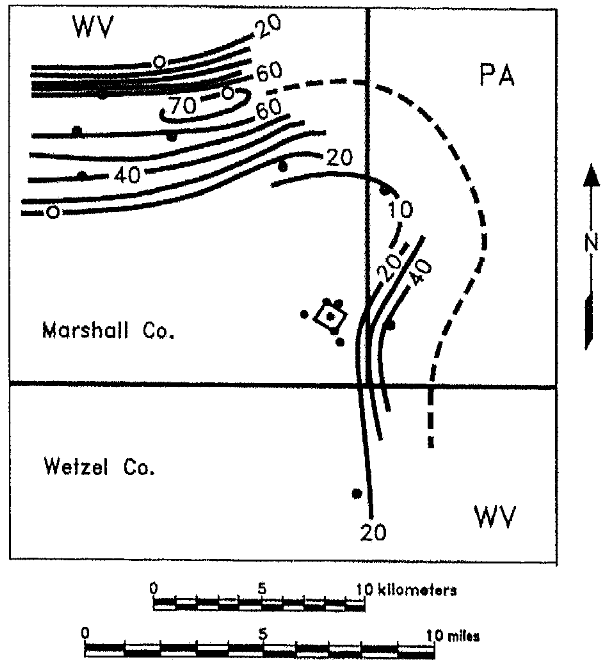

Figure 5. Isopach map of the sand overlying the Upper Freeport coal. The contours are interpreted to form a bend in a large channel system. The open circles indicate wells where the Upper Freeport coal is missing. A 10 foot contour interval is used.

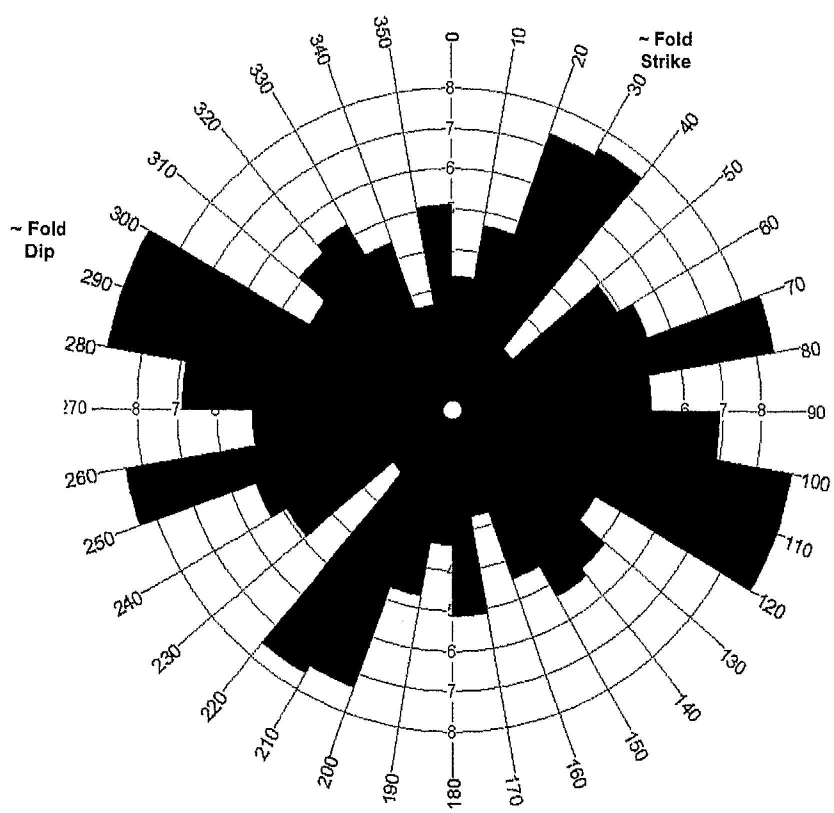

Figure 6. Rose diagram of surface fracture trends measured in rock exposures surrounding the pilot site.

We also examined the distribution of coal cleat orientations presented in Nickelsen and Hough's (1967) paper. Nickelsen and Hough (1967) present face and butt cleat orientations from Marshall County, WV and nearby areas in Ohio and Pennsylvania. The rose diagram of the cleat trends reported by Nickelsen and Hough (Fig. 7) suggests that two systematic face cleat trends are present in the area with mean orientations of N46W and N76W.

The N76W face cleat orientation coincides closely with the N74W surface fracture trend observed in the vicinity of the pilot site. Surface fractures having the N46W trend do not form a distinct cluster (Fig. 6). Butt cleat trends (Fig. 7B) measured from Nickelsen and Hough's map have mean orientation of N19E, roughly orthogonal to the face cleat trend. A minor N72E butt cleat trend is also noted in Nickelsen and Hough's data from southeast Marshall Co., near the pilot site. The N72E trend is also prominent in the surface fracture measurements made the study area.

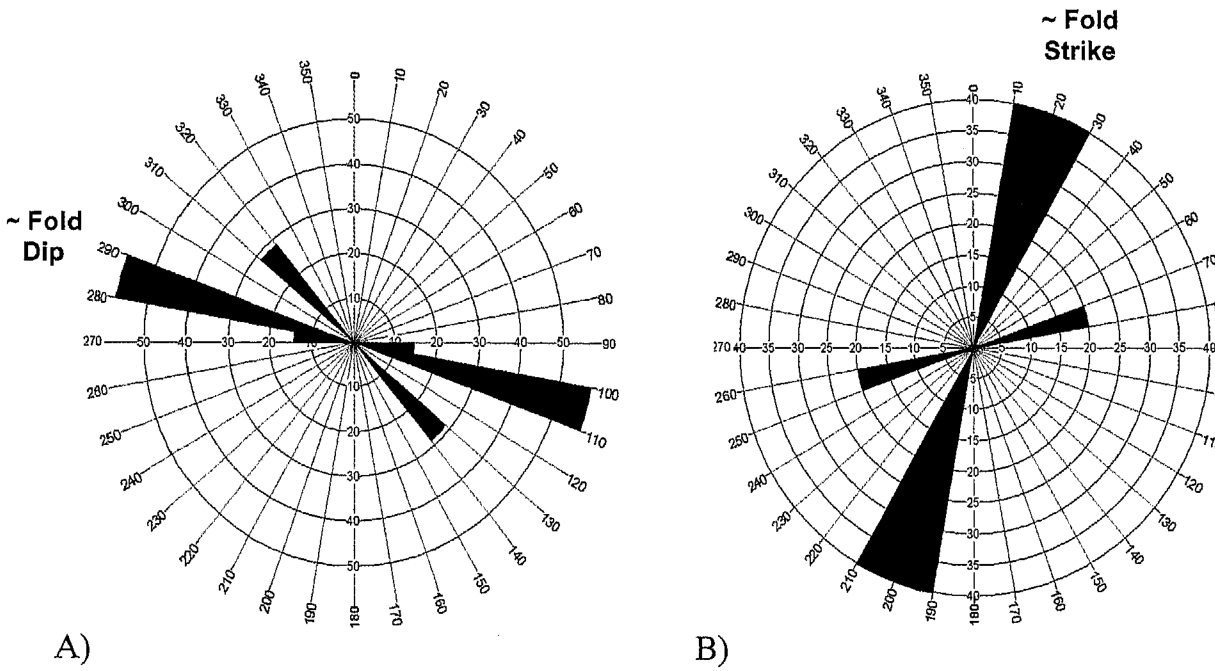

Figure 7. Rose diagram of A) face cleat and B) butt cleat trends taken from Nickelsen and Hough (1967).

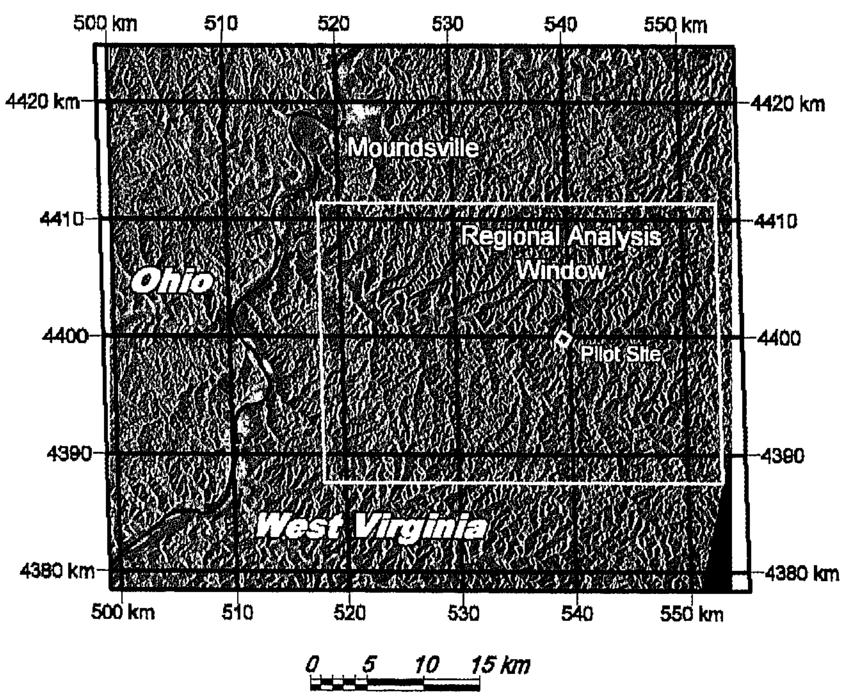

Figure 8. The general location of the area analyzed in the regional scale lineament analysis (Regional Analysis Window) is identified by the white borderline on the standard beam (25 meter pixel size) radar image. The location of the pilot site is identified by the small white-outlined square in the regional analysis window. The regional analysis window is approximately 35 by 25 kilometers in size.

LINEAMENT MAPPING AND DIRECTIONAL ANALYSIS

A 25 by 35 km area surrounding the Marshall County, WV, pilot site was selected for detailed lineament analysis using the regional scale radar, Landsat, and SPOT imagery (see area highlighted in Fig. 8). Radar lineaments mapped on the standard beam radar image are shown in Figure 9 and the directional analysis of lineament trends is shown in Figure 10. The rose diagram of radar lineaments reveals that interpreted lineaments fall into two clusters (Fig. 10). Rayleigh's test for the presence of a preferred trend suggests it is unlikely at $\alpha < 0.01$ that these clusters could form through sampling of a uniform circular distribution. One cluster has vector mean trend of N49W and another has a vector mean of N80E. The 95% confidence limits

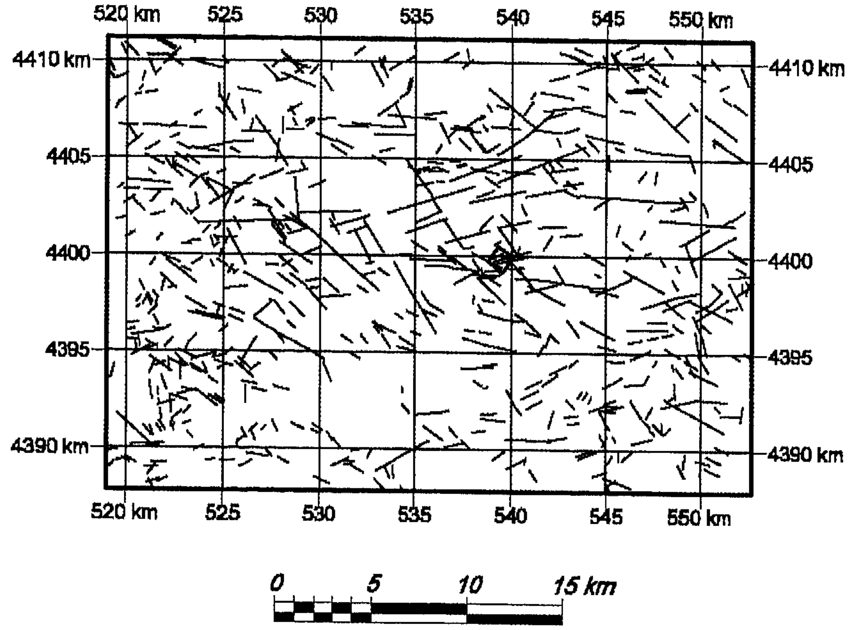

Figure 9. Locations of lineaments interpreted in the regional analysis window in the standard beam radar scene are shown in the vicinity of the pilot site. The pilot site is identified by the black-outlined square.

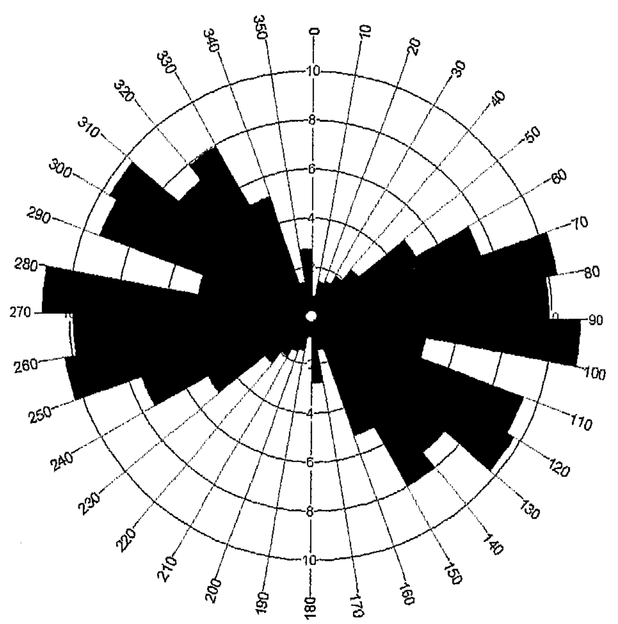

Figure 10. Rose diagram of standard beam radar lineaments reveals two clusters with mean trends of N49W and N80E.

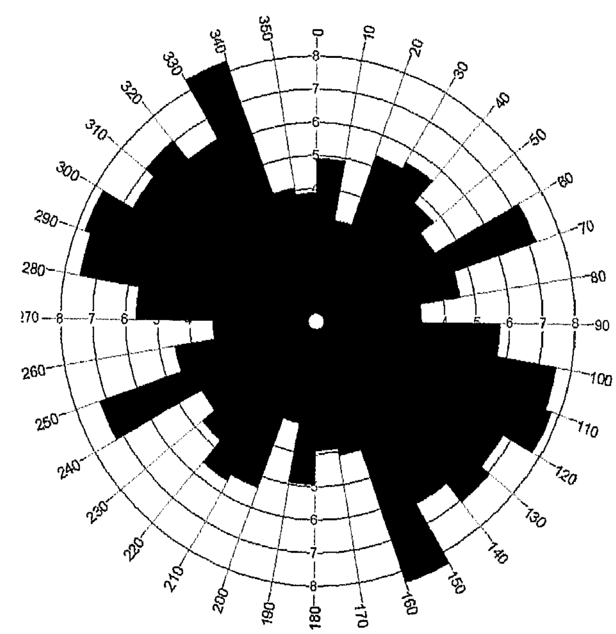

Figure 11. Lineaments mapped in the fine beam imagery reveal two clusters: a pronounced N52W trending cluster and a less pronounced N49E cluster. The 95% confidence limits on the mean orientation of these clusters are ± 4 degrees and ± 7.8 degrees, respectively.

of ± 1.83 degrees and ± 1.77 degrees respectively indicate these clusters have statistically different mean trends.

We also undertook a similar analysis of the fine beam radar image. Interpreted fine beam radar lineaments fall into two clusters (Fig. 11): one with a N52W vector mean and the other, a N49E vector mean. The 95% confidence limit on the N52W vector mean is ± 4 degrees and suggests that this cluster and the N49W cluster observed in the standard beam image have similar trend. A significant N49E trend was not observed in the standard beam data.

Rose diagrams for the various orientation data collected in this study are shown in Figure 12. The rose diagrams of lineament orientations are weighted by lineament length. Fracture and cleat lengths were not measured and their rose diagrams are frequency weighted. The mean orientations of clusters observed in these rose diagrams are tabulated for reference in Table 1. In the case of all lineament and drainage data the cluster means are the vector sum of individual lines interpreted in these data sets. Cluster means of azimuth data are the arithmetic mean. All orientations were transformed to fall in either the northeast or northwest quadrants.

Lineament analysis is often viewed with considerable skepticism. The method is subjective and the results are often ambiguous: interpreted lineaments in one type of imagery differ from those observed in other types, and lineament recognition often varies with the interpreter. In the present study, we have undertaken lineament interpretation of various types of remote sensing imagery and aerial photography to provide us with some perspectives on the potential existence of fracture zones and faults in the study area and to evaluate the potential existence of any preferred orientation in mapped lineament patterns.

The preceding directional analysis indicates that the various trends, whether surface fracture, coal cleat, or satellite-mapped lineaments, have preferred and statistically significant trends. The data can be grouped together based on similarity of scale, measured property, or by set (Table 1). The surface fracture and coal cleat trends, for example, represent outcrop measurement of fracture surface strike. Digital orthophoto lineaments generally appeared to be associated with topographic features. There appears to be some difference in the trends of the digital orthophoto lineaments with scale: at more regional scales (6 x 7km scene), three prominent trends appear; however, interpretation of a more detailed view of the orthophoto in the vicinity of the pilot site (1 x 1 km) revealed lineaments roughly dominated by a single trend. Drainage path orientations observed in the 6 x 7km scale view of the DEM data reveal the presence of multiple trends. Flow paths derived from the digital elevation data provide an unbiased view of so-called topographic lineaments. Interpretations

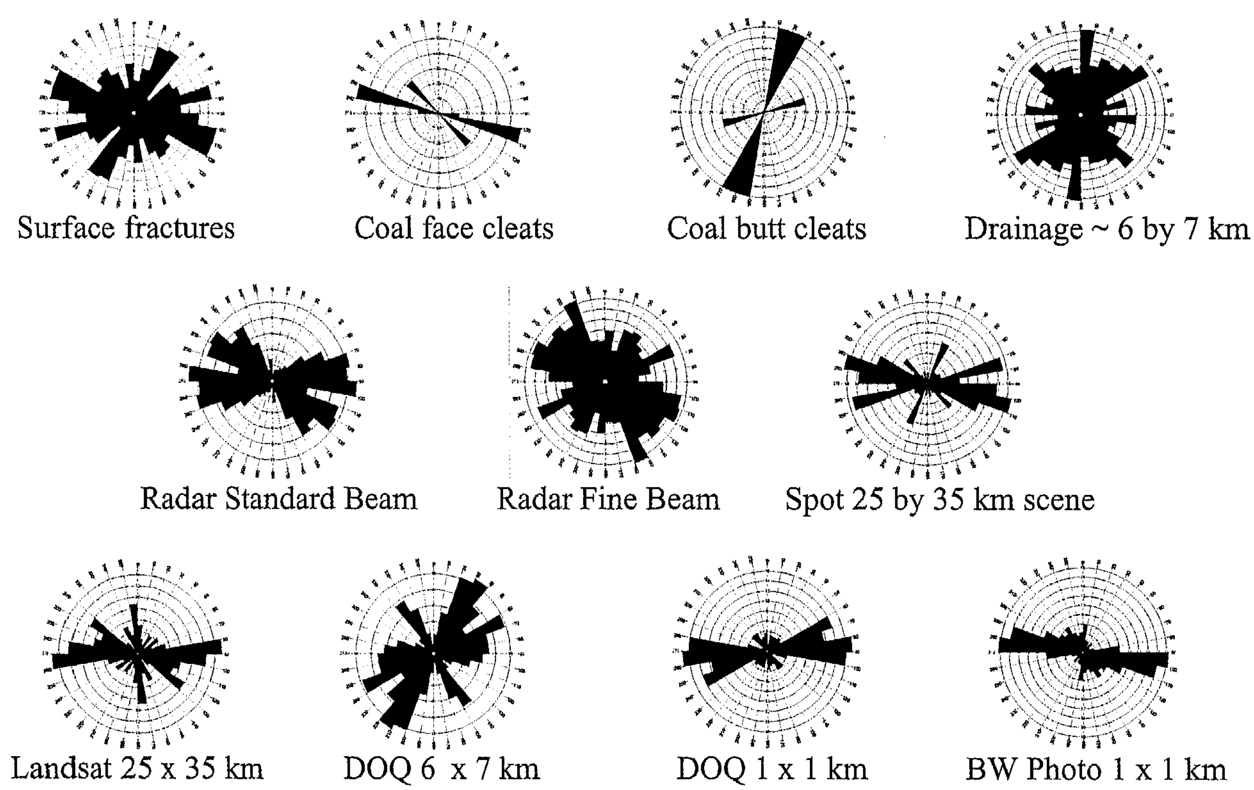

Figure 12. Rose diagrams of surface fracture, drainage, and image-interpreted lineament orientations area are presented for comparison.

Table 1. Mean orientation of lineament, cleat, and fracture clusters observed in remote sensing imagery and surface fracture data from the area surrounding the pilot site. Fracture set identification is also identified.

Set	Regional Scale (~25x35km)			Intermediate Scale (~6x7km)			Local Scale (~1x1km)		Outcrop (regional)	
	Radar	SPOT	Landsat	Radar	DOQ	DEM	DOQ	Photo	Cleats	Fracture
Acute		N77W	N79W					N80W	N76W	N74W
Dip	N49W		N56W	N52W	N32W	N33W			N46W	
			N06W			N07E				
Strike		N25E		N49E	N32E	N39E			N19E	N26E
Acute	N80E	N77E			N83E		N81E		N72E	N71E

of the orthophoto views were undertaken specifically to map linear features and did not give preference to drainage features.

STRUCTURAL INTERRELATIONSHIPS

Structure contour maps of the study area (Figs. 2 and 3) reveal that the region is gently folded with maximum bedding dip of only ½ degree or so. These folds may have formed in response to horizontal compressive stresses generated during the collision of tectonic plates. In general, three sets of fractures or joints are often associated with folds (Fig. 13). One set consists of fractures that trend parallel to fold strike. Another set consists of fractures that trend in the dip direction perpendicular to fold strike. A third set is comprised of two fracture trends that form an acute angle with the dip direction.

The strike of folds in the Marshall County area is roughly N30E. Following the model shown in Figure 13, we would expect to observe four prominent fracture orientations in rose diagrams of fractures associated with this fold orientation: 1) N30E, N60W, N30W, and N90W (or EW). These four directions coincide with fold strike, dip and two sets that form an acute angle with the dip direction. An idealized rose diagram showing these four trends is presented in Figure 14. Data for the four fracture orientations noted above were generated from random Gaussian distributions with the above means. A sample variance of 5 degrees was used.

This simple model of the relationship between fractures and

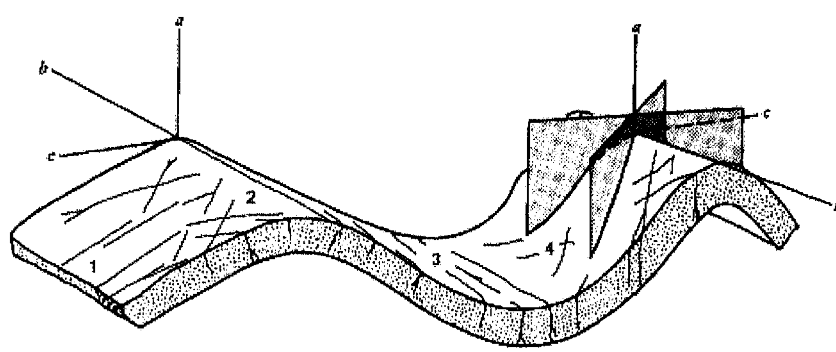

Figure 13. Fracture sets associated with folds (taken from Hobbs et al. 1976).

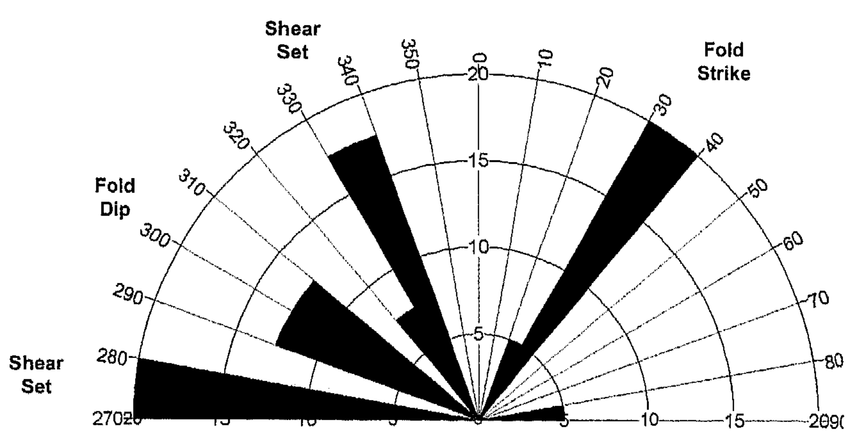

Figure 14. Idealized rose diagram showing the four systematic joint or fracture trends associated with a fold having strike of N30E.

folds can be complicated through superposition of strains resulting from multiple episodes of deformation. Only one episode of compressive deformation, the Allegheny orogeny, is believed to have produced folds in this area of the Appalachians. However, in addition to this major episode of mountain building represented by the Allegheny orogeny, significant reactivation of deeper basement faults beneath the area has also occurred (Wilson 2000). The faults in this basement complex are largely the result of Grenville (1Ga) compression and Eastern Interior (0.56Ga) extensional deformations (Shumaker and Wilson 1996). The fault systems in this basement complex are oriented roughly parallel to the near-surface folds in the area. Since the early Paleozoic system of extensional basement faults roughly parallels late Paleozoic folds, it is likely that fracture systems developed or enhanced by periodic movement on these faults would have orientations similar to those associated with the near-surface folds. However, the maximum compressive stress would be vertical and aerial views of fracture orientations would likely have a dominant trend in the strike direction. Fracture orientations could be further complicated by subsequent strike-slip movement on the deeper system of basement faults if it occurred. In addition, the system of fractures formed in the deeper basement fault system could exert some control over the movement associated with orogenesis. Fracturing during orogenesis could follow the patterns developed during earlier episodes of deformation.

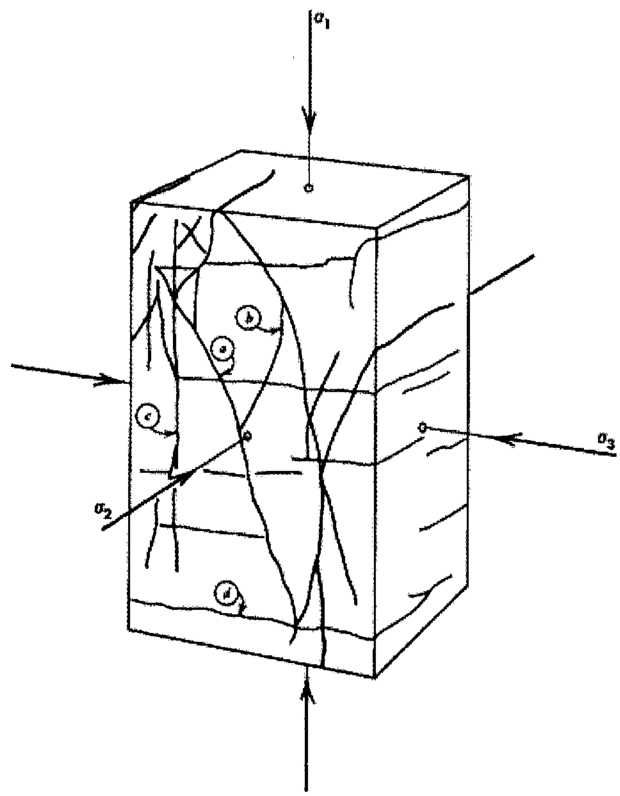

Figure 15. Fractures formed in a block of limestone deformed under triaxial loading and unloading (taken from Hobbs et al. 1976).

Experimental deformation of rock samples under triaxial loading produce the fracture sets noted above and illustrated in Figure 14. The schematic diagram in Figure 15 from Hobbs et al. (1976) represents fractures formed experimentally in a block of limestone subjected to triaxial compression ($\sigma_1 > \sigma_2 > \sigma_3$). The vertical fractures shown in Figure 15 are extension fractures that formed during unloading. The two sets of fractures that form an acute angle with σ_1 are conjugate shear fractures, and the set of horizontal fractures (those perpendicular to σ_1) formed during unloading when the position of σ_3 becomes vertical (Hobbs et al. 1976).

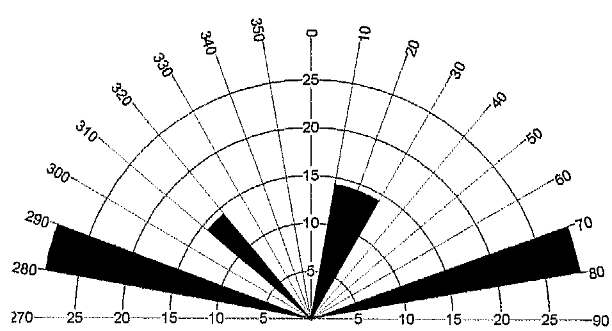

Figure 16. Mean orientations of surface fractures and coal cleats observed in the study area.

DISCUSSION OF FRACTURE AND LINEAMENT ORIENTATION DATA

In the following discussion, we examine fracture and lineament orientation data within the context of the foregoing model. Simplified rose diagrams are compiled from the cluster-means tabulated in Table 1. A rose diagram of the mean fracture and cleat orientations listed in Table 1 reveals four prominent trends consistent with regional structural trends in this part of the central Appalachians (Fig. 16). The nearly orthogonal N23E and N75W sets are interpreted to be associated with the strike and dip of regional structures (both basement and shallow detached structure) through the area. The strikes of surface folds in the surrounding area are variable, but have roughly N30E orientation. The N72E and N46W sets form an acute angle bisected approximately by the N75W set. In general, the systematic face cleat trend (N76W set) is associated with the direction of maximum compressive stress and the N72E and N46W sets are interpreted to have a conjugate shear relationship to the direction of maximum compressive stress.

The orientation of drainage patterns, or flow paths, mapped in the DEM data (Fig. 17A) is not entirely explained by the model associated with folds. It can be argued that the N39E vector mean is roughly associated with regional strike. The N33W vector mean could be associated with the conjugate shear direction. The N07E vector mean does not fit in

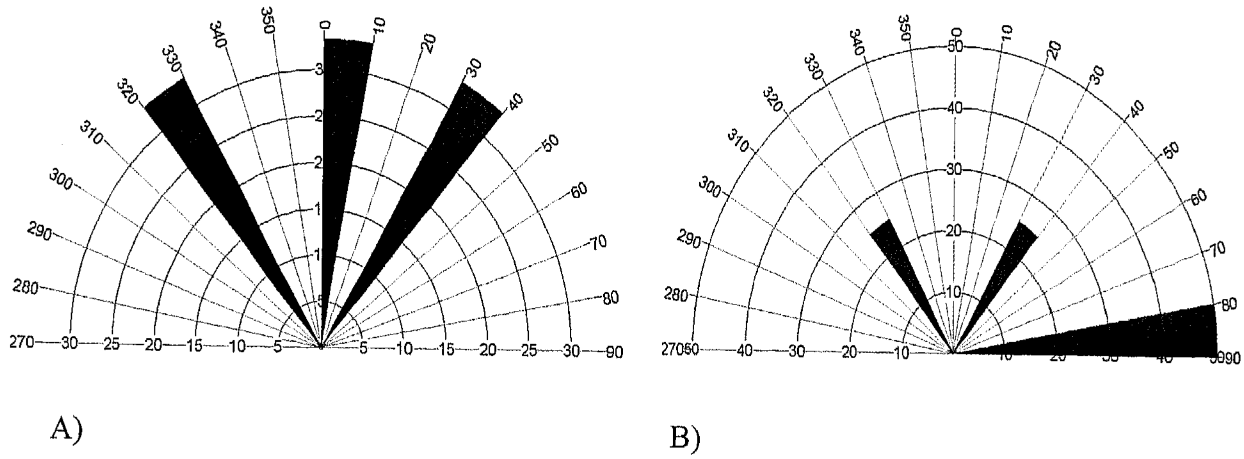

Figure 17. Mean orientations of A) DEM flow paths, and B) orthophoto lineaments.

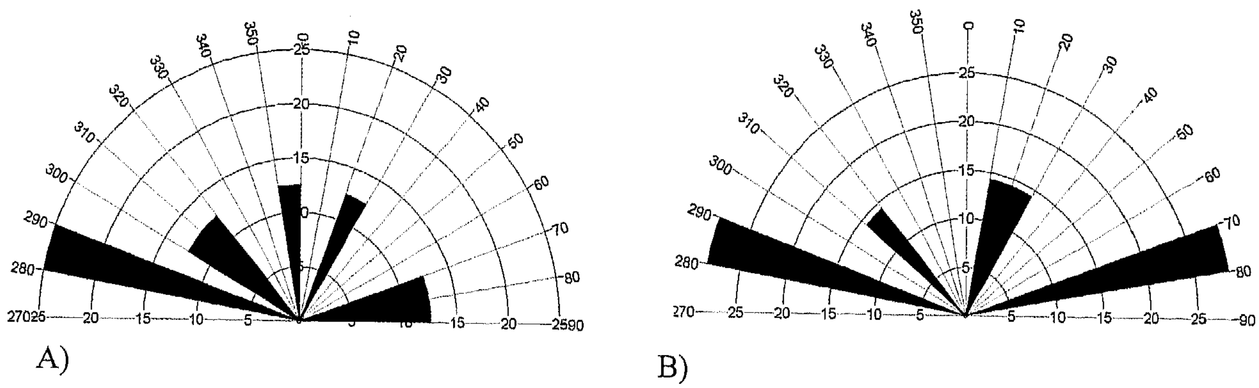

Figure 18. A) Vector mean regional lineament trends derived from radar, SPOT, and Landsat imagery. B) Mean surface fracture trends.

the context of the fold model. Prominent vector means observed in the pattern of orthophoto lineaments (Fig. 17B) are consistent with regional fold trend. The N32E mean may be related to regional strike, while the N32W and N83E vector means are interpreted to have conjugate shear relation in the direction normal to strike.

The vector means of regional scale lineaments mapped in the satellite imagery (Fig. 18A) are generally consistent with surface fracture trends (Fig. 18B). The N06W trend is an anomalous trend similar to that observed in the DEM drainage. A pronounced N80W trend is also observed in the rose diagram of lineaments (see Fig. 12, lower right) interpreted in the 1938 black and white aerial photograph of the pilot site. That orientation coincides with the inferred conjugate shear direction.

When the cluster means of all image-mapped lineaments (Table 1) are combined into a single rose diagram (Fig. 19) they form five clusters. The means of these individual clusters are, clockwise from the northwest, N79W, N44W, N01E, N36E, and N80E. The N36E and N79W trends are tentatively associated with regional strike and dip fractures, whereas the N80E and N44W trends are tentatively associated with the conjugate shear fractures. The N01E set represents an anomalous trend that is unaccompanied by a significant counterpart in the surface fracture or coal cleat orientations.

Mapped regional scale lineaments (25 x 35km scenes) in the vicinity of the pilot site (Fig. 20) have strike, dip, and both conjugate shear orientations. The rose diagram of local lineament orientations (Fig. 21) indicates that those with a northeasterly conjugate shear trend are dominant. The prominent N70-75E trending lineament zone observed in all imagery intersects the pilot site.

If the fracture zones in the area formed in response to the late Paleozoic Alleghanian orogeny they are likely to have been reactivated by subsequent extension during rifting. If these zones were initially formed during earlier episodes of basement extension and inversion, then their reactivation history is likely to include additional movement during mountain building and later rifting. In addition, we expect that surface loading, associated with sediment deposition, and unloading, resulting from surface weathering and

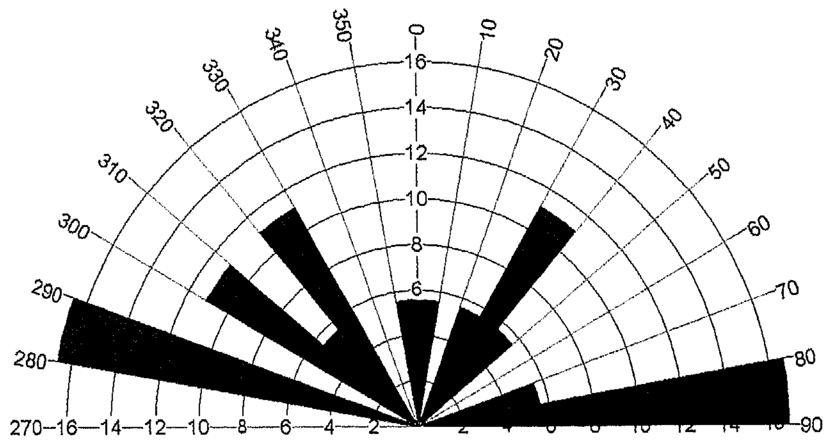

Figure 19. Composite rose diagram compiled from the cluster means of all lineament, surface fracture and coal cleat orientations observed in the region.

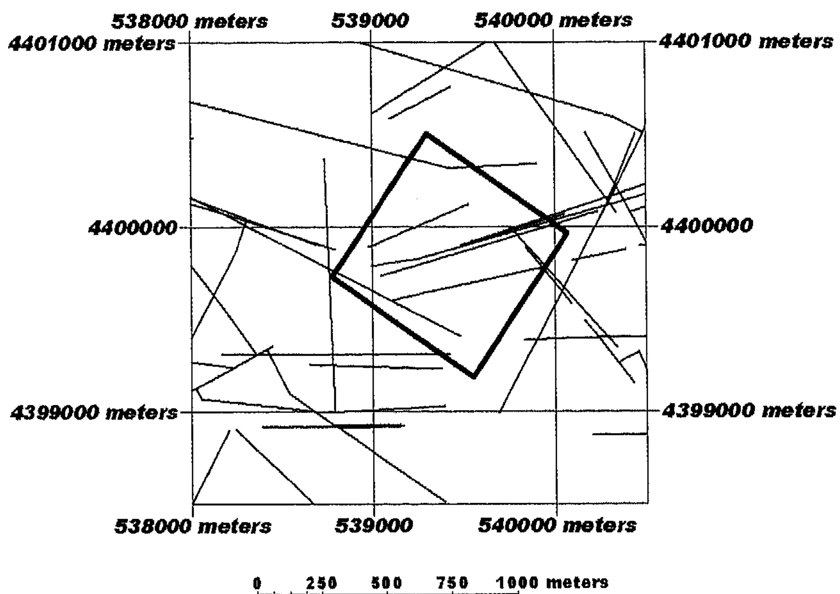

Figure 20. Lineaments mapped on radar, SPOT, and Landsat imagery are shown in the vicinity of the pilot site (outlined by the heavy black square).

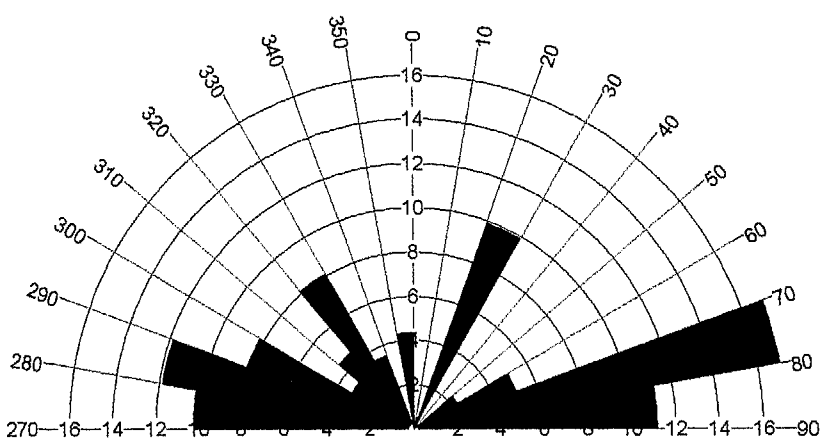

Figure 21. Rose diagram of lineament trends observed in the surrounding 2.5 x 2.5 km area of the pilot site.

erosion, will affect fracture porosity and permeability. Beaumont et al. (1988) estimate that the rocks now exposed at the surface in the area of the pilot site were once covered by approximately 8000 feet of strata. These strata were broken down over time and removed by the processes of weathering and erosion. Unloading is accompanied by isostatic rebound of the crust, which essentially floats on visco-elastic layers of the deeper lithosphere and asthenosphere. During unloading and rebound, fracture zones will serve as the locus for small amounts of movement. A complicated deformation history, including the effects of loading and unloading, could enhance or decrease permeability within existing fracture zones.

The orientation of the present-day stress field will also influence how subsurface intervals respond to injection of CO_2. Present-day principal stress orientations in the region averages about N72E. Two present-day maximum compressive stress orientations are published for the area near the Marshall Co. test site in the World Stress Map database (Reineker et al. 2003). A N96E orientation is reported 10 km to the east and a N67E orientation is reported from an area 27 km to the southwest. Over-pressuring during injection would most likely open fractures normal to the least compressive stress. Over-pressuring could open bedding-plane partings or previously existing fractures with trends roughly parallel to the maximum compressive stress. Maximum compressive stress orientations observed near the area coincide roughly with the average face cleat trend (N76W or N104E) and the dominant N70-75E lineament trend intersecting the pilot site.

The possibility that fracture zones are present at the sequestration site is suggested by the foregoing study. As noted earlier, sequestration verification requires identification and monitoring of potential migration pathways that could serve as conduits along which rapid escape of CO_2 or displaced methane into earth's atmosphere might occur. The foregoing lineament and fracture analysis provides a rapid and relatively low cost reconnaissance assessment that identifies potential fracture zones that may represent risk to the success of the pilot sequestration activity. This lineament study will help strategically locate future geophysical surveys and monitoring activities at the pilot site.

FUTURE GEOPHYSICAL ASSESSMENT

Once the environmental assessment of the pilot site is completed, surface geophysical surveys of the area will be conducted. W plan to collect a 2D grid of terrain conductivity measurements over candidate lineaments. This will provide a measure of conductivity within the upper 5 to 10 meters of the surface. A parallel set of very low frequency (VLF) electromagnetic measurements will also be collected over the same areas for comparative purposes. The VLF measurements generally provide a deeper (30 to 60 meter) view of near-surface electrical conductivity variations. Terrain conductivity soundings are also planned across anomalies that appear in contour maps of the terrain conductivity and VLF data. These soundings will help define the vertical variation of conductivity down to depths of approximately 60 meters. Acquisition of a seismic line across the site is also planned. This seismic line will provide a detailed view of subsurface structure that might adversely impact the sequestration effort.

CONCLUSIONS

Reconnaissance geologic characterization and lineament mapping were undertaken at a pilot carbon sequestration site in Marshall County, West Virginia. In this geologic sequestration test, CO_2 will be injected into an unminable coal (the Upper Freeport coal) at a depth of approximately 1400 feet beneath the surface in the area. Structure and isopach maps derived from coal exploration wells reveal that the area is mildly deformed. Maximum bedding dip in the area is less than one degree. The Upper Freeport varies in thickness from 0 to 7 feet over distances of only a few kilometers. At the pilot site the Upper Freeport is estimated to be between 2 and 3 feet thick. Sands in the interval overlying the coal have a channel-like distribution. In places, the sand appears to have scoured down into the coal, and in others, to have removed it completely.

We mapped lineaments at the site using various types of remote sensing imagery. Satellite radar images were collected over the site especially for this study. Lineaments were also mapped on Landsat, SPOT, digital elevation data, digital orthophotos, and black and white aerial photography. Lineament orientations are statistically non-uniform in distribution, and individual clusters generally have significantly different means. Considerable variability is present in the lineament orientations mapped in different imagery; however, on the whole, lineaments fall into one of 5 clusters having orientations of N79W, N44W, N01E, N36E, and N80E. Composite surface fracture and coal cleat orientations fall into 4 clusters with orientations of N75W, N46W, N23E and N72E. These fracture sets have orientations consistent with fold-induced fracturing. The N23E set lies roughly in the direction of regional strike (N32E). The N75W set coincides roughly with the dip direction. The N72E and N46W sets form an acute angle with the dip direction and are interpreted to be conjugate shear fractures. With exception of the N01E set, lineament orientations are similar to surface fracture orientations.

Although fracture and coal cleat orientations can be related to the orientations of surface folds in the area, the influence of other deformation mechanisms on fracture development cannot be ruled out. Basement faults beneath the area have trends similar to the surface folds. It seems likely that fractures observed at the surface may have developed not only in response to folding during the Allegheny orogeny, but also through episodic movement of deeper basement blocks. In addition, significant isostatic rebound of the crust in response to erosion of more than 8000 feet of surface sediment from the region following the breakup of Pangaea will also have contributed to fracture development.

In general the presence of similarity between the orientations of surface fractures and lineaments provides some support for the idea that mapped lineaments may be related to zones of increased fracture intensity. Within the context of the pilot carbon sequestration activity planned for the Marshall County site, the prominent N70-75E trending lineament that crosses through the site represents a possible migration pathway for escape of displaced methane and injected CO_2 in the Upper Freeport coal.

The reconnaissance studies presented in this paper provide important background on site geology and reveal the presence of potential fracture zones that could affect the efficacy of the carbon sequestration effort. The study serves as the basis for planning geophysical surveys at the site and will help strategically locate site monitoring activities that will provide benchmark background and long term observations of soil gas and groundwater chemistry at the site.

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